

We would like to thank the reviewers for their helpful comments. Based on their comments, we have significantly changed our approach, and included many additional analyses. A brief description of the new methodology and results is provided below, followed by our detailed response to each reviewer's questions. Reviewers' original questions/comments are in blue, and our answers are in black. Owing to the extensive changes made to the original manuscript, some comments on specific wording and styles may no longer be applicable. We will respond to them accordingly.

Synopsis of the new methodology and results

This study aims to examine whether icebergs have a significant impact on the ocean net primary productivity (NPP) at the scale of the entire Southern Ocean (SO). We examine both large and small icebergs based on two separate datasets and determine if similar impacts can be observed. We first divided the SO into four ecological zones based on their different nutrient source and profile: the continental shelf zone (CSZ), the seasonal ice zone (SIZ), the permanent open ocean zone (POOZ), and the polar front zone (PFZ). Within each zone we compared NPP for grids with and without iceberg presence. For small icebergs, we found that grids with iceberg presence in general have higher NPP than those without icebergs. However, the impact is not uniform. In the CSZ where high level of iron is supplied through glacial meltwater and sediment input from the continent and continental shelf, and phytoplankton growth is largely limited by macronutrients, the presence of icebergs does not seem to have any impact on the ocean NPP. On the other hand, Iceberg presence could significantly increase NPP in the high-nutrient low-chlorophyll (HNLC) regions. The NPP of grids with icebergs is 21% higher than those without in the SIZ, and 16% higher in the POOZ. The difference is slightly less (12%) for the PFZ where upwelling and eddy mixing could provide additional iron to the surface water, hence iron limitation is not as severe. Direct correlation between iceberg frequency and NPP is weak although statistically significant. The strongest correlation is found at the SIZ which contains over 70% of the icebergs by volume. For large icebergs, we found that the mean NPP for iceberg grids and their immediately adjacent grids are on average 10% higher than NPP of the nearby grids further away. However, the zonal response is different. The enhancement of NPP is the greatest in the high latitude zone of the CSZ and SIZ, which contains the majority of the large iceberg occurrences. Finally, we examined the secular trend of iceberg occurrence in the SO under the current climate change. For the entire period of the iceberg data, 1992-2014, both iceberg volume and frequency have shown significant increasing trends. The increasing trend is most significant for the Pacific and Indian sections of the SO, whereas the Atlantic section of the SO shows no statistically significant trend. This could be related to the greater mass loss of the West Antarctica Ice Shelf, and the relative stability of the East Antarctica Ice Shelf under present climate change. As the climate continues to warm, the Antarctic Ice Sheet is expected to experience increased mass loss as a whole, which could lead to more icebergs in the region. Based on our study, this could result in higher level of NPP in the SO as a whole, providing a negative feedback for global warming.

Reviewer No. 1

1) There seems to be a rather large disconnect in scale here that I'm having trouble understanding. It appears that most of the previous work on this subject has looked at iceberg properties and associated ocean/productivity effects at small scales – i.e. individual icebergs or icebergs within small defined areas. How do the authors justify scaling up to a hemispheric-scale analysis based on these limited findings?

Despite the great interests and several small scale areal studies suggesting increased concentrations of chlorophyll, krill, and seabirds surrounding icebergs, there seems to be a lack of large-scale studies that examine the impact of icebergs on total productivity in the SO. However, this is an important question, because in order for icebergs to have a significant role in the carbon cycle, hence serving as a possible negative feedback in the climate system, they should have an observable impact on NPP beyond the scale of individual icebergs. Therefore, this study aims to establish whether icebergs has a significant impact on marine productivity at the scale of the entire SO based on remote sensing data. In addition, most previous studies focus on large icebergs (> 18.5 km long) (Duprat et al. 2016, Helly et al. 2011). Although these large icebergs may have a big impact on productivity of surrounding area, they are relatively rare compared to much more abundant small icebergs. Tournadre et al. (2008) estimated over 8000 small icebergs (< 1km) alone in one year. Moreover, small icebergs have a much larger surface to volume ratio, providing relatively more substrate for organisms (Smith 2011). So when considered in total, they can have a big impact over much larger area in the SO. The majority of small icebergs come from the dislocation and breaking of large icebergs, and therefore serve as an important diffuse process for transport of freshwater and nutrients including iron (Tounadre et al. 2016). In this study, we examine both large and small icebergs to determine if similar impacts on the ocean net primary productivity (NPP) could be observed at the SO scale. In addition, this study also examines the secular trend of icebergs to establish whether increased icebergs could be observed with present climate change. These are important questions based on which we can evaluate whether icebergs could provide an important negative feedback for global warming.

References:

- Duprat, L. P. A., Bigg, G. R., David J., and Wilton, D. J.: Enhanced Southern Ocean marine productivity due to fertilization by giant icebergs, *Nature Geo.*, doi:10.1038/NGEO2633, 2016.
- Helly, J. J., Kaufmann R. S., Vernet M., and Stephenson G. R.: Spatial characterization of the meltwater field from icebergs in the Weddell Sea. *Proceedings of the National Academy of Sciences* 108 (14) 5492-5497, doi:10.1073/pnas.0909306108, 2011.
- Smith, K. L.: Free-drifting icebergs in the Southern Ocean: an overview. *Deep Sea Research Part II: Topical Studies in Oceanography* 58 (11): 1277-1284, doi:10.1016/j.dsr2.2010.11.003, 2011.
- Tournadre, J., Whitmer K., and Girard-Ardhuin F.: Iceberg detection in open water by altimeter waveform analysis. , *J. Geophys. Res., Oceans* 113, no. C8, doi: 10.1029/2007JC004587, 2008.

Tournadre, J., Bouhier, N., Girard-Ardhuin, F., and Rény, F.: Antarctic icebergs distributions 1992–2014, *J. Geophys. Res.*, 121(1), 327-349, doi: 10.1002/2015JC011178, 2016.

One could imagine that icebergs from different regions would have radically different properties – volume, area, number, sediment concentration, sediment composition, etc. In particular, the bioavailable iron concentration would almost surely be different across various regions – how does one then compensate for that when scaling to the entire Southern Ocean?

Multiple sources of iron exist in the SO. In the revised paper, in order to separate the impact of icebergs from some known sources, we divide our study area into four distinct ecological zones, each with different sources of nutrient supply (Fig. 1). These zones were adapted and modified from previous studies (Treguer and Jacques 1992, Moore and Abbott 2000, Ito et al. 2005), and within each zone the nutrient profile should be relatively similar. They are listed as follows:

- Continental shelf zone (CSZ): area less than 500 m in depth around the Antarctica continent and permanent ice shelves.
- Seasonal Ice Zone (SIZ): area north of the CSZ and within the mean maximum ice extent, defined by area with mean sea ice concentration greater than 70% in February. This region is delineated using the mean monthly sea ice 1979-2013 obtained from the National Snow and Ice Data Centre (ftp://sidacs.colorado.edu/pub/DATASETS/nsidc0192_seaice_trends_climo/monthly-climatology/).
- Permanent Open Ocean Zone (POOZ): area north of the SIZ and south of the Polar front zone (defined below). This zone is largely ice free throughout the year.
- Polar Front Zone (PFZ): area within 1 degree (~110km) of the polar front defined by Dong et al (2006). This is an area characterized by strong upwelling and eddy mixing.

The Subtropical Front, northern boundary of the Antarctica Circumpolar Circulation, usually defines the border of the SO. However, since few icebergs drift past the PFZ, areas of the SO north of the PFZ is not considered in this study.

References:

- Tréguer, P. and Jacques, G.: Dynamics of nutrients and phytoplankton, and fluxes of carbon, nitrogen and silicon in the Antarctic Ocean, *Polar Biol.*, 149-162, 1992.
- Moore, J. K. and Abbott, M. R.: Phytoplankton chlorophyll distributions and primary production in the Southern Ocean, *J. Geophys. Res.*, 105(C12), 28709-28722, doi: 10.1029/1999JC000043, 2000.
- Ito, T., Parekh, P., Dutkiewicz, S., and Follows, M. J.: The Antarctic circumpolar productivity belt, *Geophys. Res. Lett.*, 32 (13), L13604, doi: 10.1029/2005GL023021, 2005.

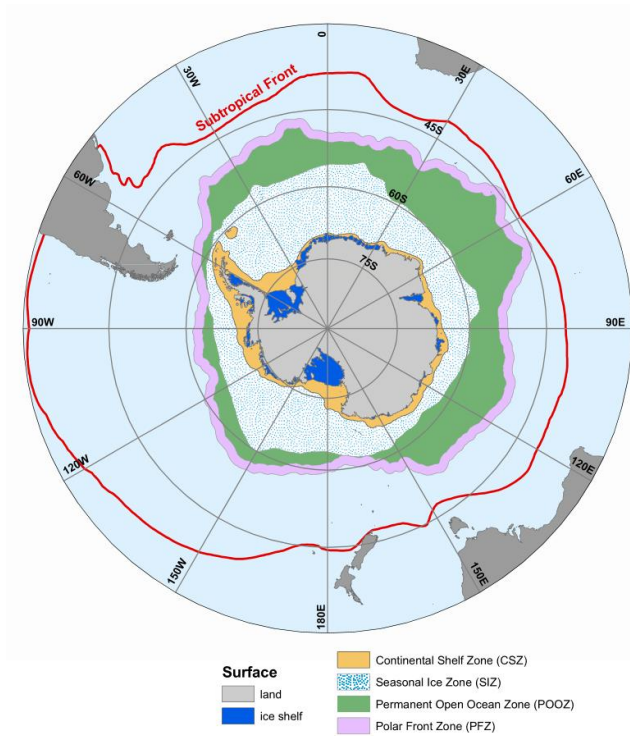


Fig. 1: Ecological zones of the Southern Ocean.

Impact of small icebergs on NPP

Unlike large icebergs which are routinely tracked and monitored through satellite scatterometer instruments, small icebergs could not easily be identified until recently. The monthly dataset of small iceberg (<3km) is obtained from Iceberg Database of the Merged Altimeter for Altiberg project for 1992-2014 (<ftp://ftp.ifremer.fr/ifremer/cersat/projects/altiberg/>). This is the first and only dataset on small icebergs. The data is generated based on the analysis of high resolution altimeter waveforms from images of 9 satellite-based altimeters (Tournadre et al., 2016). The data contains three variables: iceberg presence probability, surface area and volume. Iceberg probability of presence is defined in Tournadre et al. (2012) as “the ratio of the number of icebergs detected within a grid cell by the total number of valid satellite data samples within the same grid cell”. It is essentially normalized iceberg frequency. In the revised paper, we refer to this variable as such to make it more explanatory. Details of how iceberg surface area and volume are estimated can be found in Tournadre et al. (2012).

Figure 2a shows the spatial distribution of mean NPP (Fig. 2a) in the SO in relation to the defined ecological zones. Figure 2b shows the spatial distribution of normalized frequency for small icebergs in the SO in relation to the defined ecological zones.

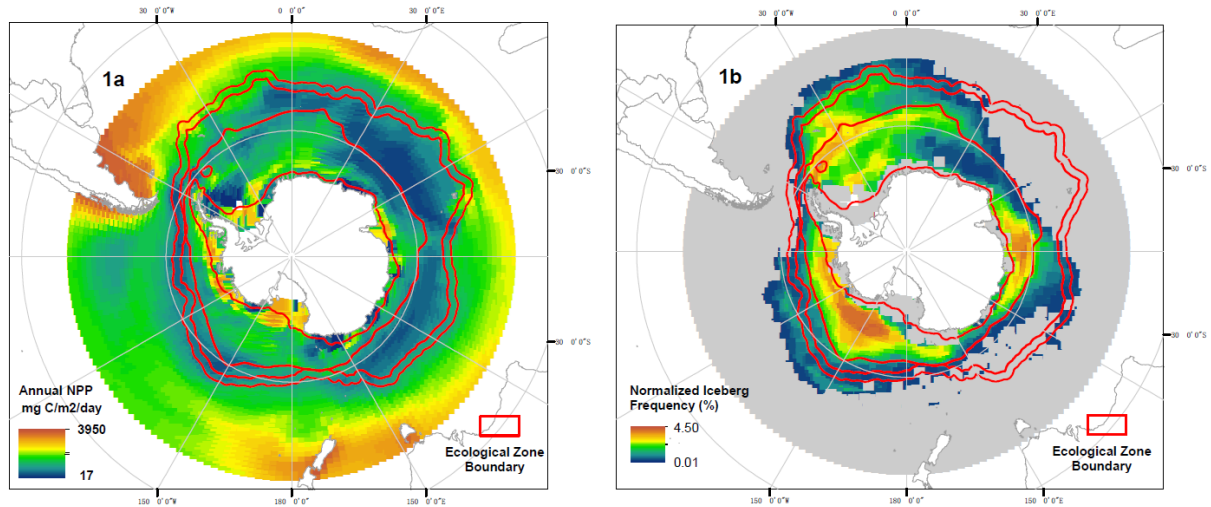


Fig. 2. Spatial distribution of annual mean NPP (a) and normalized iceberg frequency (b) in relation to ecological zones.

For small icebergs, within each zone, we compared the mean NPP for grids with icebergs and those without. Our results suggest that the presence of icebergs is associated with elevated level of productivity in most part of the SO, although their impact varies in different ecological zones. With the exception of CSZ, where there is little difference between the two, NPP in grid cells with iceberg presence is significantly higher than that in cells without icebergs. The difference is most significant for the SIZ with iceberg cell NPP 21% higher than those without. It is 16% higher for the POOZ and 12% higher for the PFZ. All differences are statistically significant based on the two-sample Student's t test.

Zones	Total area of grids with icebergs (million km ²)	Area of Productive grids with icebergs (million km ²)	Annual iceberg volume (Gt)	Annual iceberg volumes over productive water (Gt)	NPP over productive waters with icebergs (gC m ⁻² yr ⁻¹)	NPP over productive waters without icebergs (gC m ⁻² yr ⁻¹)
CSZ	0.20	0.17	103.72	88.88	112.57	113.72
SIZ	2.66	2.34	1351.11	1257.72	70.27	58.04
POOZ	1.33	1.10	370.94	315.16	65.65	56.50
PFZ	0.26	0.23	63.69	54.83	83.40	74.59

Table 1: Mean annual NPP for grids with and without icebergs 2002-2014.

Possible explanations for such differences lie in the different nutrient sources and settings in these zones. Although short in duration, the productive season of the CSZ has the highest values of primary productivity (with an annual NPP of 112.86 gC m⁻² yr⁻¹). In this zone, nutrients are largely supplied by shelf sediments derived from the continent. Elevated iron concentration has also been recorded near the coast (Johnson et al. 1997, Moore and Braucher 2008). High levels of nutrients often lead to plankton bloom observed near the coast as well as downstream of islands (Blain et al 2007, Pollard et al. 2009). In addition, Treguer and Jacques (1992) noted high

levels of macronutrients at the beginning spring, but during summer these macronutrients become depleted in the coastal waters. This seems to suggest that primary production is limited by macronutrients instead of micronutrients such as iron. As a result, the presence of icebergs does not seem to have any significant impact on productivity near the coast.

In both the CSZ and the SIZ, sea ice can supply additional iron. Lannuzel et al. (2010) suggest that iron is incorporated from the ocean into the ice during sea-ice formation, and hence the iron concentration within the sea ice can be an order of magnitude higher than in the underlying water (Lannuzel et al. 2007). However, some model studies show that the amount of iron released from sea-ice is minor compared to the sediment source (Lancelot et al. 2009, Wadley et al. 2014). This can partly explain the generally much lower productivity in the SIZ (with an annual NPP of $62.08 \text{ gC m}^2 \text{ yr}^{-1}$), despite similarly high levels of macronutrients in the water during the productive season (Treguer and Jacques 1992). In the SIZ, icebergs seem to have the largest impacts. The productivity in the grid cells with iceberg presence in general is 21% higher than those without icebergs. This large impact can also be attributed to the fact that the majority of icebergs occur in this zone: 65% of all iceberg grids and 73% of total iceberg volume occur in this zone, occupying 36% of the productive waters of this zone.

In contrast to the CSZ and the SIZ, where seasonal ice retreat often leads to stratified system (Sullivan et al. 1988), the POOZ is typically well-mixed and ice free. Mixing brings nutrient-rich water towards the surface, resulting in high supply of macronutrients in the surface water (Pollard et al. 2002). However, although nutrient rich, the POOZ is characterized by low levels of productivity. The annual mean productivity of the POOZ is the lowest among all four zones (with an annual NPP of $56.54 \text{ gC m}^2 \text{ yr}^{-1}$). It has been recognized that such production in this region is likely to be limited by the micronutrient iron, which plays an important role in chlorophyll synthesis and hence phytoplankton growth (Geider and La Roche 1994, Martin et al. 1988, Martin et al. 1990). In this area, iron released from icebergs can be particularly important. About 30% of iceberg grids (19% by volume) occur in the POOZ, occupying about 9% of its productive waters. On average, they increased the productivity of these grids by 16%.

The Antarctic Polar Front is one of several strong fronts within the Antarctic Circumpolar Current. It is characterized by a strong gradient in the sea surface temperature within the PFZ, and marks the surface transition between cold Antarctic surface water to the south and warmer sub-Antarctic surface waters to the north (Orsi et al. 1995, Moore et al. 1999, Dong et al. 2006). Meander-induced upwelling or increased eddy mixing may lead to increased fluxes of nutrients, including micronutrients such as iron, in the surface layer, particularly where the ACC interacts with large topographic features (Moore et al. 1999, Moore and Abbott 2002). Several studies have suggested that higher levels of dissolved iron in surface waters at the PF led to elevated phytoplankton production (de Baar et al. 1995, Measures and Vink, 2001). The PFZ has a mean productivity of $74.95 \text{ gC m}^2 \text{ yr}^{-1}$. Although only about 6% of the iceberg grids (3% by volume) are found in the PFZ, occupying 4% of its productive grids, iceberg presence still has an observable impact, increasing the average productivity by 12%.

This increase is lower than that observed in the SIZ and the POOZ, partly because the relative low frequency of the icebergs and partly due to the fact that the iron limitation is not as severe in the PFZ as the other two zones.

References:

- Blain, S., Qu éguiner, B., Armand, L., Belviso, S., Bombled, B., Bopp, L., Bowie, A., Brunet, C., Brussaard, C., Carlotti, F., Christaki, U., Corbi ère, A., Durand, I., Ebersbach, F., Fuda, J.-L., Garcia, N., Gerringa, L., Griffiths, B., Guigue, C., Guillerm, C., Jacquet, S., Jeandel, C., Laan, P., Lef èvre, D., Monaco, C. L., Malits, A., Mosseri, J., Obernosterer, I., Park, Y., Picheral, M., Pondaven, P., Remenyi, T., Sandroni, V., Sarthou, G., Savoye, N., Scouarnec, L., Souhaut, M., Thuiller, D., Timmermans, K., Trull, T., Uitz, J., van Beek, P., Veldhuis, M., Vincent, D., Viollier, E., Vong, L., and Wagener, T.: Effect of natural iron fertilization on carbon sequestration in the Southern Ocean, *Nature*, 446 (7139), 1070-1074, doi:10.1038/nature05700, 2007.
- de Baar, H. J. W., de Jong, J. T. M., Bakker, D. C. E., Löscher, B. M., Veth, C., Bathmann, U., and Smetacek, V.: Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean, *Nature*, 373, 412-415, doi:10.1038/373412a0, 1995.
- Dong, S., Sprintall, J., and Gille, S. T.: Location of the Antarctic polar front from AMSR-E satellite sea surface temperature measurements, *J. Phys. Oceanogr.*, 36, 2075-2089, doi: 10.1175/JPO2973.1, 2006.
- Geider, R. J. and la Roche, J.: The role of iron in phytoplankton photosynthesis, and the potential for iron-limitation of primary productivity in the sea, *Photosynth. Res.*, 39(3), 275-301, doi:10.1007/BF00014588, 1994.
- Johnson, K. S., Gordon, R. M., and Coale, K. H.: What controls dissolved iron concentrations in the world ocean? *Mar. Chem.*, 57(3), 137-161, doi:10.1016/S0304-4203(97)00043-1, 1997.
- Lancelot, C., de Montety, A., Goosse, H., Becquevort, S., Schoemann, V., Pasquer, B., and Vancoppenolle, M.: Spatial distribution of the iron supply to phytoplankton in the Southern Ocean: a model study, *Biogeosciences*, 6, 2861–2878, doi:10.5194/bg-6-2861-2009, 2009.
- Lannuzel, D., Schoemann, V., de Jong, J., Tison, J.-L., and Chou, L.: Distribution and biogeochemical behaviour of iron in the East Antarctic sea ice, *Mar. Chem.*, 106(1), 18-32, doi:10.1016/j.marchem.2006.06.010, 2007.
- Lannuzel, D., Schoemann, V., de Jong, J., Pasquer, B., van der Merwe, P., Masson, F., Tison, J.-L., and Bowie, A.: Distribution of dissolved iron in Antarctic sea ice: Spatial, seasonal, and inter-annual variability, *J. Geophys. Res.*, 115, G03022, doi: 10.1029/2009JG001031, 2010.
- Martin, J. H. and Fitzwater, S.: Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic, *Nature*, 331, 341–343, doi:10.1038/331341a0, 1988.
- Martin, J. H., Gordon, R. M., and Fitzwater, S. E.: Iron in Antarctic waters, *Nature*, 345, 156–158, doi:10.1038/345156a0, 1990.
- Measures, C. I. and Vink, S.: Dissolved Fe in the upper waters of the Pacific sector of the Southern Ocean, *Deep Sea Res.*, 48(19), 3913-3941, doi:10.1016/S0967-0645(01)00074-1, 2001.

- Moore, J. K., Abbott, M. R., and Richman, J. G.: Location and dynamics of the Antarctic Polar Front from satellite sea surface temperature data, *J. Geophys. Res.*, 104(C2), 3059-3073, doi:10.1029/1998JC900032, 1999.
- Moore, J. K. and Abbott, M. R.: Surface chlorophyll concentrations in relation to the Antarctic Polar Front: seasonal and spatial patterns from satellite observations, *J. Mar. Syst.*, 37(1), 69-86, doi: 10.1016/S0924-7963(02)00196-3, 2002.
- Moore, J. K. and Braucher, O.: Sedimentary and mineral dust sources of dissolved iron to the world ocean, *Biogeosciences*, 5(3), 631–656, doi:10.5194/bg-5-631-2008, 2008.
- Orsi, A. H., Whitworth, T., and Nowlin, W. D.: On the meridional extent and fronts of the Antarctic Circumpolar Current, *Deep Sea Res.*, 42(5), 641-673, doi:10.1016/0967-0637(95)00021-W, 1995.
- Pollard, R. T., M. I. Lucas, and J. F. Read. "Physical controls on biogeochemical zonation in the Southern Ocean." *Deep Sea Research Part II: Topical Studies in Oceanography* 49, no. 16 (2002): 3289-3305.
- Pollard, R. T., Salter, I., Sanders, R. J., Lucas, M. I., Moore, C. M., Mills, R. A., Statham P. J., Allen, J. T., Baker, A. R., Bakker, D. C. E., Charette, M. A., Fielding, S., Fones, G. R., French, M., Hickman, A. E., Holland, R. J., Hughes, J. A., Jickells, T. D., Lampitt, R. S., Morris, P. J., Nédélec, F. H., Nielsdóttir, M., Planquette, H., Popova, E. E., Poulton, A. J., Read, J. F., Seeyave, S., Smith, T., Stinchcombe, M., Taylor, S., Thomalla, S., Venables, H. J., Williamson, R., and Zubkov, M. V.: Southern Ocean deep-water carbon export enhanced by natural iron fertilization, *Nature*, 457(7229), 577-580, doi:10.1038/nature07716, 2009.
- Sullivan, C. W., McClain, C. R., Comiso, J. C., and Smith, W. O.: Phytoplankton standing crops within an Antarctic ice edge assessed by satellite remote sensing, *J. Geophys. Res.*, 93(C10), 12487-12498, doi: 10.1029/JC093iC10p12487, 1988.
- Tréguer, P. and Jacques, G.: Dynamics of nutrients and phytoplankton, and fluxes of carbon, nitrogen and silicon in the Antarctic Ocean, *Polar Biol.*, 149-162, 1992.
- Wadley, Martin R., Timothy D. Jickells, and Karen J. Heywood. "The role of iron sources and transport for Southern Ocean productivity." *Deep Sea Research Part I: Oceanographic Research Papers* 87 (2014): 82-94.

Impact of large icebergs on NPP

Large icebergs are routinely tracked and monitored. The Brigham Young University (BYU) Centre for Remote Sensing produces and maintains an Antarctica Iceberg Tracking Database (<http://www.scp.byu.edu/data/iceberg/database1.html>) for icebergs with length larger than 6 km (Stuart and Long 2011) since 1992, using six different satellite scatterometer instruments. Icebergs are identified using enhanced resolution scatterometer backscatter images. The dataset contains the daily location for all identified icebergs. We summarize the track data into monthly 1x1 degree gridded format to facility the analysis with NPP data. Large icebergs are relatively rare. For the period 2002-2014, 393 icebergs were identified in the BYU data set. Among them, 154 are icebergs larger than 18.5 km in length. They are named icebergs monitored by the National

Ice Centre. The other 239 are smaller icebergs between 6 and 18.5 km. Their tracks are presented in Fig. 3a, and the summarized gridded count data in Fig. 3b. The majority of large icebergs concentrate near the coastal region of Antarctica, where they are calved from the major ice shelves, such as the Ross, Filchner, Ronne, Larsen, and Amery. Large number of icebergs are also present in the south Atlantic section of the SO, originated mostly from the ice shelves in the Weddell Sea.

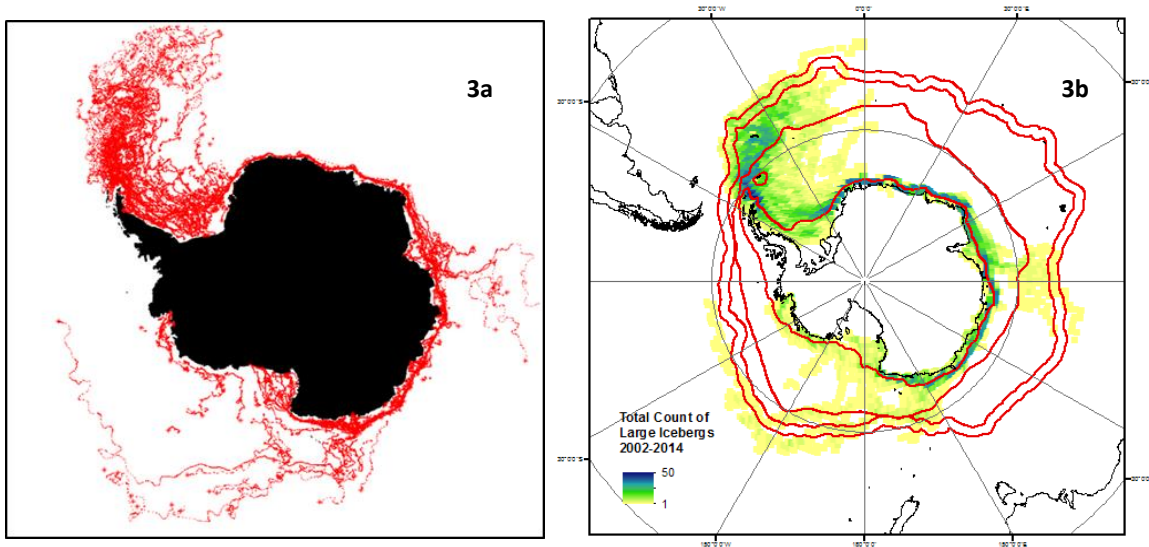


Fig. 3: Spatial distribution of large icebergs. (a) all iceberg tracks between 2002 and 2014. (b) the gridded count of iceberg occurrences between 2002 and 2014.

Since large icebergs are relatively rare, at certain point in time, they cover very small portion of the ocean surface. It is therefore not appropriate to adopt the same approach used in studying small icebergs. We use a different approach instead. We first summarize the track data into monthly snapshots of 1x1 degree grid of iceberg counts. The great majority of the grids only gets 1 large iceberg. Very rarely were more than one large iceberg present in a grid at a given month. For each iceberg occupied grid, we select a 7x7 degree (49 grids) window around it. Within the window, we identify all grids with icebergs (iceberg grids), grids immediately adjacent to iceberg grids (adjacent), and the rest of the grid within the window (nearby grids). We calculate the mean NPP for each group for a single iceberg grid, and repeat the same operation for all iceberg grids at monthly timescale. We then compare the mean NPP of these three groups to see if they are significantly different. Pair-wise t test is used to establish the statistical significance of the difference between groups. The difference is summarized by ecological zones, and their seasonal variations examined.

Based on this methodology, we calculated the mean NPP each of the three groups at monthly timescale. Results are summarized by ecological zones (Table 2). Most of the iceberg grids are located in the CSZ and the SIZ, but their frequency is still relatively low, at 73 and 60 grids per year respectively. In general, the difference in mean NPP between iceberg grids and adjacent grids are fairly small, but the mean NPP of combined iceberg and adjacent grids are significantly (about 10%) higher than the nearby grids. This pattern is fairly consistent in most

of the ecological zones with the only exception of the POOZ, where iceberg/adjacent grids have similar NPP as the nearby grids. Seasonally, the most significant increase of NPP from surrounding grids occurs in the most productive months in the austral summer (December, January and February). The general enhancement of NPP near icebergs is consistently found with both small and large icebergs, although the zonal response is different. With small icebergs, the largest enhancement is seen in zones relatively poor in iron such as the POOZ and the SIZ, whereas the effect in the CSZ is not significant. The large icebergs, on the other hand, seem to increase NPP more in the higher latitudes such as the CSZ and the SIZ. However, the low frequency of large icebergs makes it difficult to establish reliable statistical relationship. Moreover, the coarse spatial resolution (getting even coarser at lower latitudes of the POOZ and PFZ) could make it harder to detect enhancement of NPP near large icebergs.

Zone	Mean NPP of iceberg grids (mgC m ⁻² d ⁻¹)	Mean NPP of adjacent grids (mgC m ⁻² d ⁻¹)	Mean Diff.	p value	Mean NPP of iceberg and adjacent Grids (mgC m ⁻² d ⁻¹)	Mean NPP of nearby grids (mgC m ⁻² d ⁻¹)	Mean diff.	p value	No. of Iceberg grids per year
CSZ	241.41	240.79	0.62	0.84	241.54	214.62	27.17	0.00	73.08
SIZ	206.05	210.66	-4.61	0.05	208.74	188.72	20.03	0.00	60.92
POOZ	151.13	148.93	2.19	0.25	149.27	149.14	0.13	0.94	14.23
PFZ	248.78	257.69	-8.91	0.02	255.72	242.66	13.06	0.02	3.77
Total	219.15	220.87	-1.72	0.33	220.39	199.17	21.31	0.00	152

Table 2: Mean NPP of iceberg grids, adjacent grids and nearby grids.

2) The most recent work on the subject (Duprat et al., 2016) focused on large icebergs and their potential ocean impact. The authors make the assumption (lines 30-35) that the majority of small icebergs are associated with large ones, and therefore that total iceberg concentration should reveal similar impacts on ocean productivity. It's not clear to me what the basis is for this assumption. What is all or most of the sediment and hence available iron is limited to the large bergs? Smaller ones may simply be fragments that were never in contact with the bed surface. I'll readily admit here that I'm not an expert on iceberg processes, but this assumption is fundamental to the authors approach and it just seems unfounded to me.

Most previous studies focus on large icebergs (> 18.5 km long) (Duprat et al. 2016, Helly et al. 2011). Although these large icebergs may have a big impact on productivity of surrounding area, they are relatively rare compared to much more abundant small icebergs. Tournadre et al. (2008) estimated over 8000 small icebergs (< 1km) alone in one year. Moreover, small icebergs have a much larger surface to volume ratio, providing relatively more substrate for organisms (Smith 2011). So when considered in total, they can have a big impact over much larger area in the SO. The majority of small icebergs come from the dislocation and breaking of large icebergs, and therefore serve as an important diffuse process for transport of freshwater and nutrients including iron (Tounadre et al. 2016). Therefore, in this study, we examine both large and small icebergs to determine if similar impacts on the ocean net primary productivity (NPP) could be observed at the SO scale. Our results show that small icebergs indeed have a quite significant impact on the SO NPP.

References:

- Duprat, L. P. A., Bigg, G. R., David J., and Wilton, D. J.: Enhanced Southern Ocean marine productivity due to fertilization by giant icebergs, *Nature Geo.*, doi:10.1038/NGEO2633, 2016.
- Helly, J. J., Kaufmann R. S., Vernet M., and Stephenson G. R.: Spatial characterization of the meltwater field from icebergs in the Weddell Sea. *Proceedings of the National Academy of Sciences* 108 (14) 5492-5497, doi:10.1073/pnas.0909306108, 2011.
- Smith, K. L.: Free-drifting icebergs in the Southern Ocean: an overview. *Deep Sea Research Part II: Topical Studies in Oceanography* 58 (11): 1277-1284, doi:10.1016/j.dsr2.2010.11.003, 2011.
- Tournadre, J., Whitmer K., and Girard-Ardhuin F.: Iceberg detection in open water by altimeter waveform analysis. , *J. Geophys. Res., Oceans* 113, no. C8, doi: 10.1029/2007JC004587, 2008.
- Tournadre, J., Bouhier, N., Girard-Ardhuin, F., and Rény, F.: Antarctic icebergs distributions 1992–2014, *J. Geophys. Res.*, 121(1), 327-349, doi: 10.1002/2015JC011178, 2016.

3) The remote sensing product used to estimate iceberg probability is described briefly, but again I am struggling to understand the connection between iceberg probability (presumably a derived product and not a direct measurement) and the relevant information in this case – namely the amount of iron going into the water. Moreover, a broad-scale gridded remote sensing product seems rather coarse to evaluate small-scale processes. Again, I am not a remote sensing expert, and perhaps the Tournadre et al. 2012 product is a gold standard in the field, but its application here may be somewhat misleading.

Although large icebergs are routinely tracked and monitored through satellite scatterometer instruments, small icebergs could not easily be identified until recently. The monthly dataset of small iceberg (<3km) is obtained from Iceberg Database of the Merged Altimeter for Altiberg project for 1992-2014 (<ftp://ftp.ifremer.fr/ifremer/cersat/projects/altiberg/>). This is the first and only dataset on small icebergs. The data is generated based on the analysis of high resolution altimeter waveforms from images of 9 satellite-based altimeters (Tournadre et al., 2016). The data contains three variables: iceberg presence probability, surface area and volume. Iceberg probability of presence is defined in Tournadre et al. (2012) as “the ratio of the number of icebergs detected within a grid cell by the total number of valid satellite data samples within the same grid cell”. It is essentially normalized iceberg frequency. In the revised paper, we refer to this variable as such to make it more explanatory. Details of how iceberg surface area and volume are estimated can be found in Tournadre et al. (2012).

References:

- Tournadre, J., Girard-Ardhuin, F., and Legré, B.: Antarctic icebergs distributions, 2002–2010, *J. Geophys. Res.*, 117, C05004, doi:10.1029/2011JC007441, 2012.

Tournadre, J., Bouhier, N., Girard-Ardhuin, F., and Rény, F.: Antarctic icebergs distributions 1992–2014, *J. Geophys. Res.*, 121(1), 327-349, doi: 10.1002/2015JC011178, 2016.

4) My concerns about scaling and data products aside, the results of the statistical analyses are just not that compelling. There is a positive correlation between NPP and iceberg probability (not presence or concentration, as the authors write), but in all the cases the variance explained by iceberg probability is so small it's hard to imagine any physical significance. And in particular, the variance explained by temperature vs. icebergs makes the iceberg effect quite small. What of other variables? Ocean productivity could be equally linked to any number of other factors (e.g., wind stress, upwelling, circulation, etc.) – why did the authors choose just temperature (and icebergs) for the MLR analysis? And of course, old adage that correlation does not prove causation applies here – even with a significant correlation between icebergs and NPP (albeit with 2% of variance explained), the authors provide no argument for the linkage and a SO scale.

Based on your comment, we redesigned our methodology, as outlined above. Therefore, in the revised paper, regression model is not used. However, we did examine the direct correlation between NPP and iceberg frequency within each ecological zone. The correlation is small, although statistically significant. We discussed some reasons why this is the case.

In order to further examine the quantitative relationship between NPP and icebergs, we conduct the correlation analysis between the two factors. Normalized iceberg frequency is chosen over iceberg volume because it seems to better correlate with NPP. The possible reason is that for large icebergs basal melting is small compared to their breaking into smaller icebergs (Tournadre et al. 2015). These smaller icebergs act as an important diffuse process for nutrient transport. Therefore, iceberg frequency may have a more direct impact on NPP than total iceberg volume. We calculate Pearson's correlation coefficient (r) for annual total net production and the annual mean iceberg frequency. The use of annual data eliminates the seasonal cycles that exist in both variables, which can artificially inflate the significance of correlation. Given that both variables are positively skewed, we also tried non-parametric rank correlation Spearman's rho. Both methods yielded similar results, with Spearman's rho giving slightly higher correlation than Pearson's r , indicating the existence of non-linear correlation. We perform the correlation analysis in two ways. First, we calculate the correlation coefficient between annual production and iceberg frequency at each grid point (local correlation), so that we can control it for spatially varied factors such as solar radiation, length of day, and ocean circulations. We then summarize the correlation coefficients by ecological zones. Second, we calculate a single correlation coefficient for annual productivity and iceberg frequency of all grid points within a zone (zonal correlation), and compare the strength of correlation between zones.

Results of local correlation between annual NPP and iceberg frequency at each grid points are presented in Fig. 4 and summarized in Table 3. Only Pearson's r is reported, as Spearman's rho gives similar results.

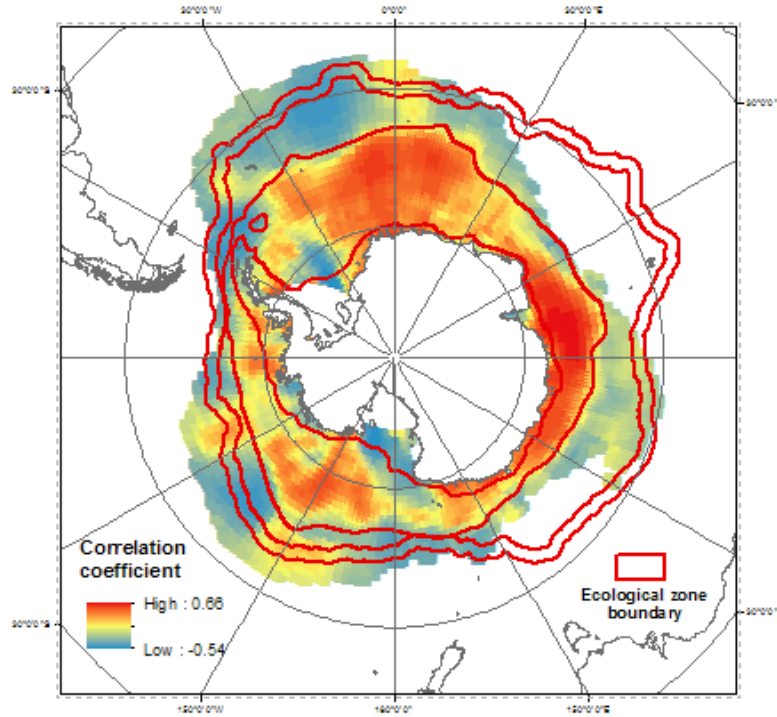


Fig. 4. Temporal correlation between annual NPP and normalized iceberg frequency.

Zone	Local correlation (Pearson's r)							Global correlation	
	Min.	1st Quarter	Median	Mean	3rd Quarter	Max.	**% of grids Significant	Pearson's r	Spearman's rho
CSZ	-0.40	-0.06	0.10	0.07	0.20	0.66	16.30	0.16*	0.23*
SIZ	-0.55	0.04	0.15	0.14	0.25	0.57	33.49	0.18*	0.22*
POOZ	-0.36	-0.04	0.06	0.04	0.13	0.43	21.54	0.13*	0.16*
PFZ	-0.27	-0.10	0.00	-0.01	0.09	0.23	14.50	0.12*	0.14*

Table 3: Correlation between annual total primary production and iceberg frequency.

Note: * Correlation significant at 0.01 level.

** % of grids with iceberg presence for which correlation is significant at 0.05 level.

Most significant positive correlations occur in the SIZ, with the median coefficient r at 0.15. The correlation is statistically significant at 0.05 level for 33% of the grids in this zone. The correlation is much weaker for other zones (Tab. 3). Within each zone, there is a wide range of coefficient values, both positive and negative. Only a small portion of the correlations are statistically significant. This is largely because when summarized at annual timescale, the size of the data is largely reduced. With the data coverage of only 13 years, at each grid point, the number of data is 13 or less, making it difficult to establish a reliable correlation with statistical significance. When data are pooled together, zonal correlation shows much higher statistical strength, indicated by very low p values for the correlation in all zones. Correlation coefficients, however, are still relatively low (Tab.3). In

general, it seems that correlation is more positive and stronger in the high latitude zones of the SIZ and the CSZ, and weaker in the POOZ and the PFZ.

The general low level of correlation is not surprising for several reasons. First of all, the correlation is only calculated between NPP and small iceberg frequency. The occasional presence of large icebergs could sometimes skew the relationship. However, the relatively low frequency of large icebergs makes it difficult to incorporate them into the same correlation analysis. The direct correlation between NPP and iceberg frequency could also be weakened by other sources of Fe (such as meltwater, sedimentary, and upwelling sources), variable phytoplankton Fe:C quotas, light and silicate limitations, the atmospheric Fe dissolution kinetics, aeolian Fe sources and transport pathways. In addition, the statistical relationship between the SO NPP and icebergs also depends on the forms of Fe in icebergs. Most previous studies focus on direct measurement of soluble iron. However, Hassler and Schoemann (2009) found no direction link between soluble and bioavailable Fe because organic ligands have the differential effects on the solubility and the bioavailability. Several studies seem to suggest that organic colloidal Fe provides an important pool to sustain Fe bioavailability to phytoplankton (e.g. Nodwell and Price, 2001; Chen et al., 2003; Wang and Dei, 2003). Finally, icebergs themselves could have other effects on NPP. For example, Arrigo and van Dijken (2004) observed that icebergs could have negative effects on the polar marine ecosystems in some occasions. Many of these icebergs have long residence times, and hence are likely to have been located in highly productive coastal waters during the peak growing seasons of austral spring and summer. Their presence can alter normal advection patterns of annual sea-ice, and hence the fraction of open water available for phytoplankton growth. All these factors could have contributed to a relatively weak correlation between the SO NPP and iceberg occurrences. For more detailed studies on the impact of icebergs relative to some of the factors listed above, we need to develop quantifiable indicators for these factors and incorporate them into statistical modelling. Such indicators could include distance to the coast, distance to aeolian dust sources along transport pathways based on atmospheric circulation patterns, proportions of bioavailable iron to total soluble iron from iceberg case studies, ocean circulation patterns etc.

References:

- Arrigo, K. R., and van Dijken, G. L.: Annual cycles of sea ice and phytoplankton in Cape Bathurst polynya, southeastern Beaufort Sea, Canadian Arctic. *Geophysical Research Letters* 31, no. 8
doi:10.1029/2003GL018978, 2004.
- Chen, M., Dei R. C. H., Wang W. X., and Guo, L.: Marine diatom uptake of iron bound with natural colloids of different origins. *Marine Chemistry* 81 (3), 177-189, doi:10.1016/S0304-4203(03)00032-X, 2003.
- Hassler, C., and Schoemann, V.: Bioavailability of organically bound Fe to model phytoplankton of the Southern Ocean. *Biogeosciences* 6 (10), 2281-2296, doi:10.5194/bg-6-2281-2009, 2009.
- Nodwell, L. M., and Price, N. M.: Direct use of inorganic colloidal iron by marine mixotrophic phytoplankton. *Limnology and Oceanography* 46 (4): 765-777, doi:10.4319/lo.2001.46.4.0765, 2001.
- Tournadre, J., Bouhier, N., Girard-Ardhuin, F., and Rény, F.: Large icebergs characteristics from altimeter waveforms analysis. *Journal of Geophysical Research: Oceans* 120 (3): 1954-1974, doi:10.1002/2014JC010502, 2015.

Wang, W.X., and Dei, R. C. H.: Bioavailability of iron complexed with organic colloids to the cyanobacteria *Synechococcus* and *Trichodesmium*. *Aquatic Microbial Ecology* 33 (3): 247-259, doi:10.3354/ame033247, 2003.

5) The discussion section provides a useful summary of all the reasons why there may be such a small statistical effect of icebergs on productivity, and indeed the authors cite studies suggesting that the presence of icebergs may in fact decrease local productivity. In light of all of this, I find the final 5 lines of the conclusion section to be unsupported by the existing analysis and results. Overall I think the authors need to either a) include a significant number of additional analyses to bolster their arguments, or b) carefully consider what conclusions can actually be drawn from the existing analysis, and re-write the paper and title accordingly.

Thank you for your helpful suggestions. We have redesigned our study and included many more new analyses, as explained in details above. Our results seem to suggest that both large and small icebergs are associated with elevated levels of NPP in the SO. However the level of enhancement differs in different ecological zones, as we outlined above.